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Published in:
28th European Conference on Optical Communication, 2002. ECOC 2002.

Link to article, DOI:
10.1109/ECOC.2002.204334

Publication date:
2002

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Bjarklev, A. O., Hansen, K. P., Hansen, T. P., Hougaard, K. G., Knudsen, E., Libori, S. E. B., Lægsgaard, J., Dybendal Nielsen, M., Riishede, J., & Tanggaard Larsen, T. (2002). Photonic Crystal Fibres - the State-of-the-Art. In *28th European Conference on Optical Communication, 2002. ECOC 2002.* (pp. 1-2). IEEE. https://doi.org/10.1109/ECOC.2002.204334

PHOTONIC CRYSTAL FIBRES – THE STATE-OF-THE-ART

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Abstract *Photonic crystal fibres having microstructured air-silica cross sections offer new optical properties compared to conventional fibres. These include novel guiding mechanisms, unique spectral properties and non-linear possibilities. Recent results within the field are reviewed.*

Introduction

Photonic Crystals were first proposed in 1987 [1,2]. Today, micro-structured optical fibres appear to be one of the most promising areas to use Photonic Crystals. This specific field of research is today about five years old [3,4], and it addresses the issue of periodically microstructured optical fibres with a high-index contrast (they typically consists of air holes in a silica background material). These fibres have been given several names ranging from holey fibres, microstructured fibres, photonic crystal fibres (PCFs), to photonic bandgap (PBG) fibres. In this presentation, we will review some of the most recent results within the field, covering a non-exhaustive list of subjects such as attenuation in PCFs, fibre Bragg gratings in PCFs, laser and amplifier PCFs, and highly non-linear PCFs.

Attenuation of light in Photonic Crystal Fibres

As in the case of optical fibres based on standard technology, the attenuation in photonic crystal fibres relying on modified total internal reflection (TIR) has primary contributions from scattering and absorption effects. However, PCFs offer some additional challenges when aiming for low loss properties. In the case of an air-silica fibre, the effective index of the guided mode is intrinsically below that of the silica background, causing the mode to be leaky in finite structures. This kind of confinement loss in PCF structures depends on the air-filling fraction in the structure and the number of holes present to confine the guided mode. These mechanisms have been described and modeled by several groups [5,6] showing that the confinement loss can always be reduced by adding more periods to the structure. Among the more practical issues, using the stack-and-pull fabrication process [7] impose some complications compared to a solid synthetic perform, since areas close to the core are composed of building blocks with potentially contaminated surface areas. The first photonic crystal fibres fabricated had losses in the range of several tens [8] or even hundreds of dB/km [9]. However, the level of attenuation has since then been drastically reduced and in 2001, results on a PCF with a loss of 1.3 dB/km at 1550 nm were published [10]. In year 2002, the attenuation level reached 1 dB/km [11], and no fundamental reasons prohibits PCF technology from completely eliminating the current excess attenuation relative to standard fibre technology.

Fibres relying on the PBG effect still exhibit quite dramatic losses compared to the index guiding fibres, with typical values which are in the range of a few dB/m [12,13].

Fibre gratings in Photonic Crystal Fibres

The combination of fibre gratings and photonic crystal fibres has successfully been used to realize a new range of grating based optical devices. Among the most innovative applications are the hybrid polymer-silica optical fibres, where the air holes surrounding the core-region are filled with a polymer. Thereby, the spectral position of the cladding mode resonances may be tuned by changing the temperature [14]. Another possibility related to fibre grating technology is the so-called air-clad fibres, where a ring of large air holes effectively separates the inner cladding from the surroundings. These fibres may be used for long-period gratings devices, where light is coupled to non-leaking cladding modes [15]. Traditionally, fibre-gratings are fabricated by exposing a germanium doped fibre core to a periodic pattern of UV-light. However, recently a structural long-period grating has been presented [16], where the grating has been created by making a periodic collapse of the air-holes along the length of the PCF.

Photonic Crystal Fibre lasers and amplifiers

As first reported in [17], PCFs may also be used in laser and amplifier configurations, by doping the PCFs with rare-earth ions. Using PCFs as rare-earth-doped fibres, may lead to significant advantages compared to standard fibre based solutions. With large-mode-area PCFs, it is possible to fabricate lasers and amplifier with high damage thresholds as well as low non-linearities [18]. High-power cladding-pumped lasers may also be designed, where large air holes in the outer cladding forms a high-NA inner cladding [19]. The unique dispersion properties of PCFs allow for design of soliton lasers at wavelengths below 1300nm, which may be used for generation of femtosecond pulses at wavelengths below 1300nm, using soliton-self-frequency shift (SSFS) [20].

The first experimental observation of Raman effects in a PCF was presented at ECOC 2001, and later in [41]. Here, a 75m highly non-linear PCF was used as an amplifier in the 1610—1640 nm range. The same fibre was also used to demonstrate all-optical modulation.

Highly non-linear Photonic Crystal Fibres

Of the large variety of photonic crystal fibres, the highly non-linear PCF is the most commonly used and that within a large field of applications ranging from spectroscopy and sensor applications to the directly telecom oriented. The high non-linear coefficient and designable dispersion properties makes these fibres attractive for many non-linear applications of which supercontinuum generation has been the most intensively investigated [21-23]. The continua have been used in applications like optical coherence tomography [24], spectroscopy, and metrology [25]. Supercontinua covering several octaves as well as multi-watt output have been demonstrated [26]. Considerable effort has been made to develop better understanding of the complex interplay of nonlinear processes behind supercontinuum generation and many of the basic mechanisms (e.g., soliton fission [27,28], self-phase modulation [29], four-wave-mixing and stimulated Raman scattering [22]) are today understood.

Highly non-linear fibres with zero-dispersion at 1.55μm have long been pursued as these fibres are very attractive for a range of telecom applications such as 2R Regeneration [30], multiple clock recovery [31], parametric amplifiers (OPAs) [32], pulse compression [33], wavelength conversion [34], all-optical switching [35] and supercontinuum-based WDM telecom sources [36]. Recently, we have demonstrated a highly nonlinear photonic crystal fibre with zero-dispersion wavelength at 1.55μm and a non-linear coefficient of 18 $(W{\cdot}km)^{-1}$ - two times that for standard nonlinear fibre [37]. The fibre has been utilized in an all-optical nonlinear optical loop mirror, demultiplexing a bit-stream of 160GB/s down to 10 GB/s. This was achieved with only 50m of fibre, compared to the 2.5km of dispersion shifted standard fibre normally required [38,39]. New production processes, where the fibre preforms are extruded in soft lead-glass has also been demonstrated for fabrication of highly non-linear fibres [40].

Conclusions

Due to the unique ability of photonic crystal fibres to provide novel cut-off, spot-size, and dispersion properties, the potential future applications are numerous. We have emphasized some of the fundamental properties of PCFs and indicated some of their potential future applications. Important issues, such as low losses, low polarization-mode dispersion, and good control of the properties in the communication windows still need to be addressed for PCFs to exhibit their full potential. For specific applications, however, PCFs have already proven their worth and more areas will follow as better control of the key parameters is attained.

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